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APPLICATION OF ENHANCED GAS RECOVERY TO COAL MINE GAS DRAINAGE SYSTEMS

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ABSTRACT: Over the past 30 years rapid development of the coalbed methane industry in the USA and Australia has stimulated research into the mechanisms that control gas migration in coal seams. A technique for enhancing gas recovery from coal was trialed in the San Juan Basin, USA in 1998. The results showed a sustained 500% increase in gas production rates. The technique involves using an injectant gas to stimulate coalbed gas diffusion and increase seam permeability. This paper describes the technique, the potential applications for coal mining and presents a conceptual field trial for an Australian coal mine to demonstrate the effectiveness in partially drained coal mine workings.

INTRODUCTION

In 1990 Puri and Yee published a paper describing a coal bed methane reservoir as analogous to an absorbent bed. Adsorbent bed regeneration techniques are described as follows (Puri and Yee 1990):

- Pressure depletion – equating to "drawdown" of a coalbed methane gas well, or drilling of an underground gas drainage hole at atmospheric pressure.
- Thermal desorption – reducing the capacity of coal to adsorb gas by increasing the temperature of the coal (not practical for an underground coal mine).
- Displacement desorption – stimulating desorption by displacement with a more strongly adsorbing gas (CO_2)
- Inert gas stripping – stimulate desorption by flushing the absorbent bed (coal seam) by a non- adsorbing or weakly adsorbing gas nitrogen (N_2) to increase concentration gradient.

Most subsequent investigations of enhanced gas recovery have revolved around the theory of the mechanisms and economics in relation to coalbed methane gas. This paper explores the possibility of enhanced gas recovery utilizing an inert gas stripping technique in relation to coal mine gas drainage.

BACKGROUND

Gas drainage objectives in coal mines

Pre-drainage of gas in an underground coal mine is generally conducted for one or more of the following reasons:

- Management of an outburst hazard
- Management of development rib emission
- Management of frictional ignitions (both longwall and development)
- Maintenance of ventilation contaminants to acceptable levels (CH_4, CO_2, H_2S)

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In general it is the residual gas content of the coal, after gas drainage operations have been conducted, which is important for coal mine operators. The residual value may be a pre-determined gas content for an outburst threshold or may be a level at which the problems described above are considered manageable (typically 2 m^3/t) (Packham 2005).

Achieving specific residual gas content is not a primary objective for coal bed methane (CBM) operators. For a CBM operator, gas production cost is the primary driver, consequently any processes that incur costs, such as the use of an injectant gas to enhance gas production are cautiously examined (Stevenson, Pinczewski and Downey 1993; Reeves, Davis and Oudinot 2004).

In the Hunter Valley, Australia, examples exist where developed longwall reserves have been sterilised as a consequence of gas drainage lead times (Robertson 2008). Likewise in the Illawarra southern coalfield, potential coal reserves may have to be sterilised due to gas drainage limitations (Black 2007). Clearly the economic considerations for enhanced gas recovery differ between the coalbed methane industry and the coal mining industry.

GAS DRAINAGE MECHANISM

In order to explain the process of enhanced gas recovery it is desirable to understand the mechanism of gas production from a coal seam. Two processes control the rate of gas recovery from a coal seam under pressure depletion as a means of drainage, Darcy's law in relation to gas and water flow through the cleat system and Fick's Law in relation to diffusion of the adsorbed gas from the coal matrix into the cleat.

Darcian Flow

Darcy's Law describes a 1-D, single phase flow through a porous medium (coal seam) in the following manner:

$$v_x = -\frac{k_x}{\mu}\left(\frac{\partial P}{\partial x} - \rho g_x \frac{\partial D}{\partial x}\right) \qquad (1)$$

Volumetric flux in the x direction, v_x, is a function of seam permeability, k_x, the fluid viscosity, μ, and the incremental pressure drop. The pressure drop relates to the difference in gas drainage borehole pressure and the seam gas pressure. Seam permeability is a dominant parameter for gas production rates. In Australian longwall mining environments the coal seams are typically comparatively level, as a consequence gravitational effects on gas flow are negligible.

Gray (1987) described permeability of a coal in relation to the changes in effective stress in the coal seam, where, if water is removed from the cleat, the matrix blocks are less constrained and tend to compress the cleat. This process, referred to as cleat compression, leads to a reduction in permeability. As the fluid pressure in the cleat system falls, gas desorption occurs. The release of gas from the matrix into the cleat subsequently causes the matrix to shrink and a reduction in effective horizontal stress. In terms of permeability changes, the two processes, cleat compression and matrix shrinkage tend to cancel each other. Gray relates the matrix shrinkage to effective stress in terms of a linear change in strain for a change in sorption pressure.

Palmer and Mansoori (1998) proposed a relationship for relative changes in permeability using the cubic relationship between permeability and porosity (cleat volume)

$$\frac{k}{k_o} = \left(\frac{\Phi}{\Phi_o}\right)^3 \qquad (2)$$

where k_o and Φ_o are reference permeability and reference porosity respectively. Equation 2 reads that permeability normally depends on pore throat volume, the more open the cleat the greater the permeability. Palmer and Mansoori (1998) show the relative change in porosity in response to change in reservoir pressure is given by:

$$\frac{\Phi}{\Phi_0} = 1 - \frac{c_m}{\phi_0}(p - p_0) + \frac{\varepsilon_l}{\phi_0}\left(\frac{K}{M} - 1\right)\left(\frac{\beta p}{1+\beta p} - \frac{\beta p_0}{1+\beta p_0}\right) \quad (3)$$

Where c_m is matrix compressibility, K is bulk modulus, M is unconstrained axial modulus. The three parameters are derived from the coal geo-mechanical properties of Young's modulus and Poisson's Ratio. The terms ε_l and β are parameters matching volumetric strain caused by matrix shrinkage resulting from gas desorption. Reservoir pressure and initial reservoir pressure are p and p0 respectively.

Change in coal bed permeability in relation to change in effective stress is described by Seidle (Seidle, Jeansonne and Erickson 1992):

$$k = k_o e^{-3c_f(\sigma - \sigma_o)} \quad (4)$$

where the parameter, c_f, is cleat-volume compressibility. Shi and Durucan (2004) developed a relationship to enable calculation of change in horizontal effective stress resulting from changes in reservoir pressure and desorption of gas from the coal:

$$(\sigma - \sigma_o) = -\frac{\nu}{1-\nu}(p - p_o) + \frac{E}{3(1-\nu)}\varepsilon_l\left(\frac{p}{p+P_\varepsilon} - \frac{p_0}{p_0+P_\varepsilon}\right) \quad (5)$$

where ε_l and P_ε are matrix shrinkage constants, ν **and** E are the Poisson's ratio and Young's Modulus of the coal, respectively. Initial or reference horizontal stress and pore pressure are σ_0 and p_0, respectively. The two terms on the right hand side of the equation relate to cleat compression and matrix shrinkage respectively.

Volumetric shrinkage strain is considered in both the Palmer/Mansoori and Shi/Durucan formulations to be related to the Langmuir type relationship of matrix strain at maximum adsorbed gas content and the gas content pressure at which half of the maximum strain occurs:

$$\Delta\varepsilon_s = \varepsilon_l\left(\frac{\beta p}{1+\beta p} - \frac{\beta p_0}{1+\beta p_0}\right) = \varepsilon_l\left(\frac{p}{p+P_\varepsilon} - \frac{p_0}{p_0+P_\varepsilon}\right) \quad (6)$$

where $P_\varepsilon=1/\beta$. Shi and Durucan (2005) further developed this relationship to account for matrix swelling (as may occur where a gas adsorbs onto the coal matrix in enhanced gas drainage). Assuming the pressure of the free gas in the cleat is in equilibrium with the adsorbed gas, then:

$$\Delta\varepsilon_s = \alpha_s(V - V_0) \quad (7)$$

where α_s is the volumetric shrinkage/swelling coefficient for a specific gas (i.e. a seam gas, methane or an injectant gas such as nitrogen), V corresponds to the gas content at reservoir pressure, p; V_o is the gas content at initial reservoir pressure p_o. V and V_o can be determined using the Langmuir isotherm (Zuber 1996):

$$V = \frac{V_L \beta p}{\beta p + 1} \quad (8)$$

where β is the Langmuir constant, and V_L is the Langmuir volume defining the adsorption isotherm for a single gas in a specific coal seam. This allows the change in effective horizontal stress to be determined resulting from cleat compression and matrix shrinkage or swelling due to change in pore pressure:

$$(\sigma - \sigma_o) = -\frac{\nu}{1-\nu}(p - p_o) + \frac{E\alpha_s V_L}{3(1-\nu)}\left(\frac{\beta p}{1+\beta p} - \frac{\beta p_o}{1+\beta p_o}\right) \quad (9)$$

It can be seen that change in permeability of a coal seam can be related to either change in porosity (equation 3) or effective horizontal stress (equation 5) and that both formulations are dependent on change in reservoir pressure. The effect of matrix swelling, resulting from adsorption of an injectant gas into the coal may also be determined (equation 9).

In an enhanced gas drainage process using nitrogen as an injectant, the coal matrix desorbs one gas, generally methane or carbon dioxide, and adsorbs nitrogen. The net matrix shrinkage effect is thus determined by the volumetric shrinkage coefficient, α_s and the Langmuir isotherm parameters for the desorbing and adsorbing gasses.

Diffusional Flow

Diffusion of gas from the coal matrix into the cleat system may be described by the modified Fick's law (Zuber 1996):

$$q_{gm} = \frac{8\pi D V_m}{s_f^2}(C_m - C(p)) \quad (10)$$

where gas production rate q_{gm}, is a function of matrix volume, V_m, and the difference between the matrix gas concentration, C_m, less the equilibrium concentration at the matrix cleat boundary C(p). The diffusion coefficient, D, and fracture spacing s_f, are normally resolved by the use of desorption time, τ, which is derived from gas content testing.

$$\tau = \frac{s_f^2}{8\pi D} \quad (11)$$

It is significant that the gas production rate is a function of difference in the gas concentration rather than the gas pressure. In a primary production (pressure depletion), the gas composition in the matrix is the same as the gas composition in the cleat, then difference between C_m and C(p) *is* proportional to the difference between the cleat pressure and adsorbed gas pressure. If however the cleat system is flooded with an inert gas, such as nitrogen, then difference in concentration of the seam gas between the matrix and cleat is significantly increased.

Relative Permeability

A third property which regulates the gas flow through the cleat system is the relative permeability of gas and water within the cleat at varying water saturation levels. In simple terms, when the cleat system is saturated with only water no gas will flow; as the water saturation decreases the effective permeability of gas slowly increases and gas may begin migrating through the cleat (Figure 1). This is the reason why coal seams must be dewatered for successful gas drainage. In relation to enhanced gas recovery, where an injectant is introduced into a cleat system the coal matrix may be compressed and the cleat volume increased.

Because water is only slightly compressible the water volume in the cleat system remains roughly constant but the cleat volume increases, resulting in an apparent

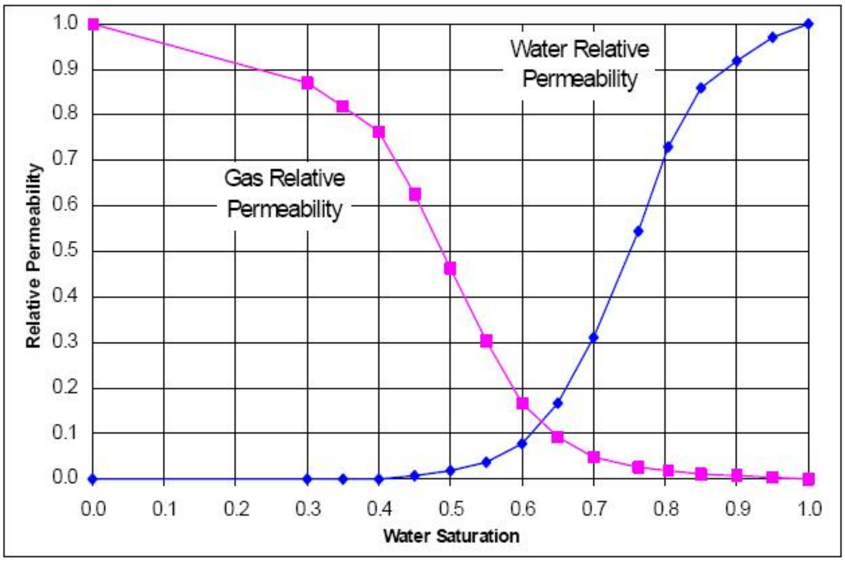

Figure 1 - Relative Permeability Curve for gas and water (permeability <1mD) (SIMED2 handbook 2003 pp.16)

reduction in water saturation. The effect is not only to increase absolute permeability but to reduce the cleat water saturation and thus improve the gas relative permeability. (Gray 1987; Stevenson Pinczewski and Downey1993; Mavor and Gunter 2004).

1. Increased permeability resulting from a change in effective horizontal stress or cleat porosity (Equations 3, 5 and 9)
2. Increased concentration gradient between the matrix and cleat interface and thus diffusion rate (Equation 6)
3. A reduced water phase saturation in the cleat system resulting in an improved effective permeability to the gas phase.

FIELD TRIALS

Coal Mine Field Trials

There are no documented cases of an injectant gas being used for enhanced gas recovery in coal mine gas drainage systems. Two references to the possibilities that nitrogen may provide in relation to coal mine gas drainage focus on the potential for improved drainage in low permeability environments (Thakur 2006; Brunner 2007).

Thakur (2006), suggested that gas flooding using nitrogen or carbon dioxide may be a solution to drainage in low permeability (<1mD) environments. Brunner (2007), claimed that for a 0.1mD permeability reservoir, nitrogen enhanced drainage would achieve a 50% gas content reduction in 7.2 months compared to 12 months for hydraulic fracture stimulation, and 24 months for traditional pressure depletion. Brunner does not provide site charaterisation details or well/borehole geometry.

Enhanced coalbed methane (ECBM) field trials

Nitrogen has been used as an injectant in three ECBM field trials. The trials were conducted to examine the potential for CO_2 sequestration with associated enhanced methane recovery. Nitrogen injection was conducted to develop an understanding of the behaviour of the gas in coal seams.

Tiffany trial, San Juan basin, Colorado, US

The Tiffany trial was conducted in an existing CBM operation which utilized vertical wells drilled to intersect 4 seams of ~14.3m total thickness at an average depth to top of the highest seam of 926m (Reeves and Oudinot, 2004). The production wells were spaced 320 acre. CBM primary production began in 1983; ECBM utilizing nitrogen began in 1998 and concluded in 2002. During the trial the methane production rate increased by fivefold (Figure 2). Initial seam permeability was assumed to be 8 mD, and porosity of 0.2%. An anticipated feature of the trial was the nitrogen breakthrough at the production wells, and the reduced water flow rate at the production wells.

Fenn-Big Valley trial, Alberta, Canada

The Fenn-Big Valley trial occurred between 1998 and 2000. The trial involved two wells, one of which was an existing oil well which had been drilled through coal measures, the other well was purpose drilled. The oil well was re-completed to allow access to a Medicine River seam at a depth of ~1259m. Both wells were subject to CO_2 injection subsequently experiencing losses in injectivity. Injection trials using nitrogen and flue gas demonstrated increases of absolute permeability from initial conditions of 1.2mD to 13.8mD for nitrogen injection and 0.985mD to 23.7mD for the flue gas injection (Mavor, Gunter and Robinson 2004). Mavor describes '*the injection ballooned the natural fracture system and substantially increased the permeability*'.

Yubari trial, Hokaido, Japan

The Yubari trial in the Ishikari coal field, Japan, was a CO_2 sequestration trial conducted between 2003 and 2008 (Shi, Durucan and Fujioka 2008). The trial involved drilling two wells to access a coal seam at about 890m depth. The injection well (IW-1) was subject to a period of initial pressure depletion, followed by multi-well production tests involving the injection of CO_2 at IW-1 and subsequent monitoring of pressure, flow and gas composition characteristics at production well, PW-1. The results from the CO_2 injection trials indicated a significant loss in injectivity due to matrix swelling and associated permeability loss, (a similar effect had been observed in a CO_2 ECBM trial in the San Juan Basin). Permeability fell from 1mD to 0.1mD due to CO_2 injection. In an attempt to improve the CO_2 injection rate N_2 was injected at IW-1. Modelling of the results indicated that an improvement in well block permeability from 0.1mD to 40mD was achieved. This improvement in permeability enabled a temporary four-fold increase in subsequent CO_2 injection.

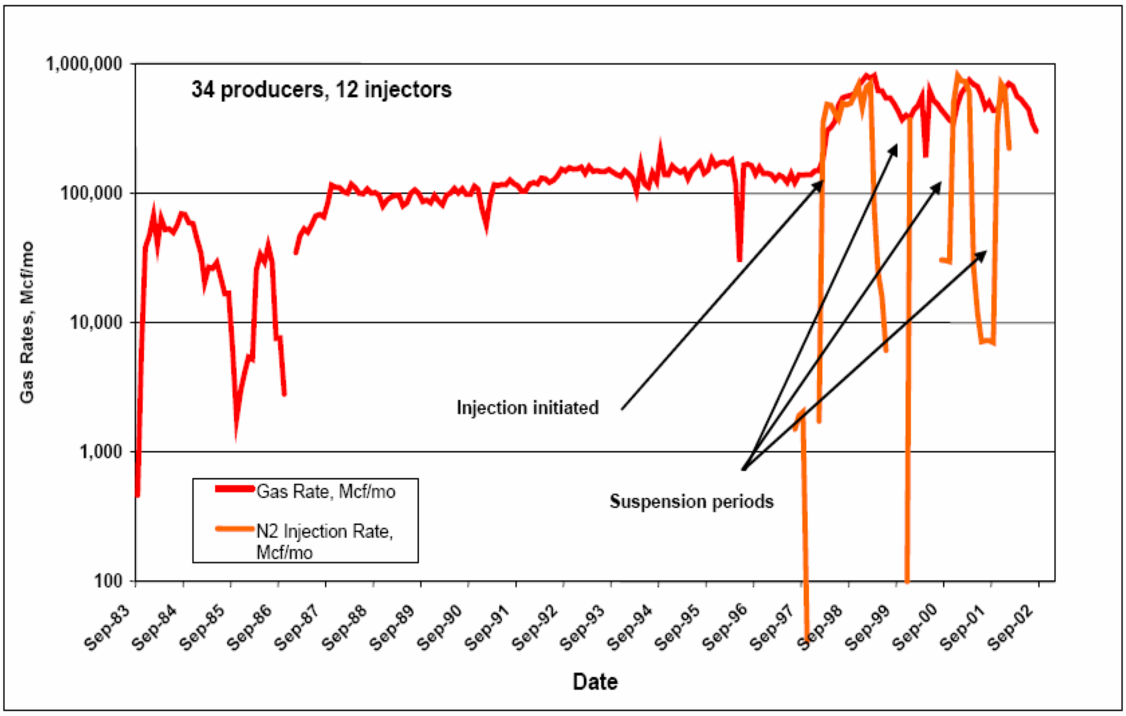

Figure 2 - Coal seam methane production and nitrogen injection gas rates for the Tiffany project (after Reeves and Oudinot 2004)

The trials all indicate improved permeability resulting from nitrogen injection, in the case of the Tiffany trial improved gas production. On the basis of the theoretical affect of nitrogen as an injectant in an enhanced gas system and from the ECBM field trial results it is reasonable to assume similar effects may be achievable in coal mine gas drainage systems.

CONCEPTUAL APPLICATION TO COAL MINE GAS DRAINAGE SYSTEMS

Coalmine gas drainage system may be considered as either surface based or underground based. Surface drainage systems in Australia predominantly utilise surface to inseam (SIS) holes, using medium radius drilling techniques. Underground drainage systems involve drilling groups of horizontal holes typically <600m long from purpose driven stubs off development roadways.

Surface Drainage Systems

SIS holes involve the drilling of an inclined hole from the surface through overburden to enter the target seam at close to seam dip. After entering the seam, the SIS hole is drilled to intersect a vertical well typically 1-2 km down dip. A pump is installed in the vertical well to dewater the SIS hole. The use of vertical wells independent of a SIS lateral for pre-drainage is not common in the Australian coal mining industry. SIS holes are generally drilled parallel to development roadways. The ability to conduct SIS drilling from the surface provides the opportunity for drainage times to be several years.

Where parallel SIS holes are prepared for pre-drainage of a proposed development roadway a simple application of enhanced gas recovery would be to use one SIS hole as an injector and on SIS hole as a producer well (Figure 3). This geometry is likely to have effective drainage between the wells, ie the coal in which the proposed development roadway is to be driven, however may be less effective in draining seam gas in the longwall block side of the SIS holes. This arrangement may be suited to an environment where a high risk of frictional ignition is present.

The same configuration of gas drainage wells may be used in relation to specific regions identified with inadequate drainage. When gas drainage is being conducted primarily for management of an outburst hazard, development roadway drivage is prohibited unless residual gas contents are below pre-established outburst threshold values. The gas content residual value is often determined by a vertically cored borehole into the pillar in advance of the development drivage.

High residual gas contents may arise due to lack of drainage time; unusually high virgin gas content or unusually low localised permeability. Where a 'compliance' core returns a result that is not below the outburst threshold value the options available to mine management are to allow more time for gas drainage to occur, to drill further gas drainage holes from underground to accelerate the drainage, or to adopt a remote mining technique such as shotfiring. Each option has significant scheduling and cost implications for longwall operations. An alternative may be to use an enhanced gas recovery process utilizing the compliance borehole as an injection well (Figure 4).

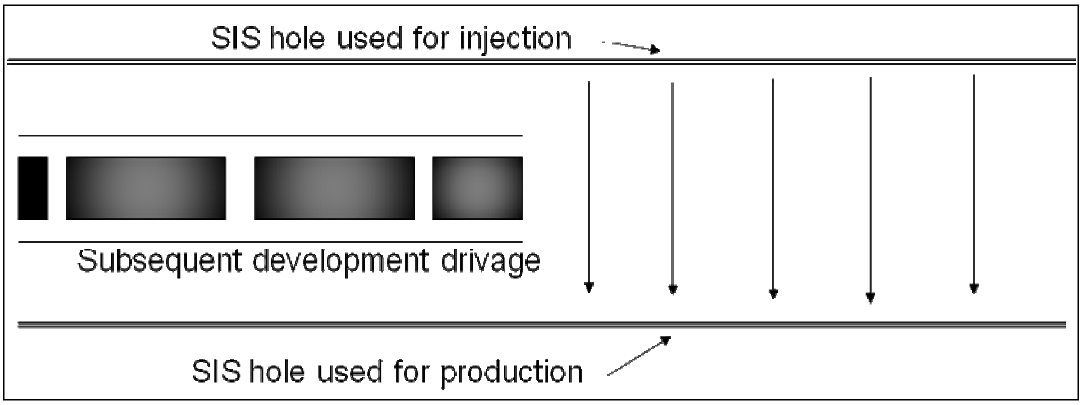

Figure 3 - Parallel SIS holes as injector and producer wells

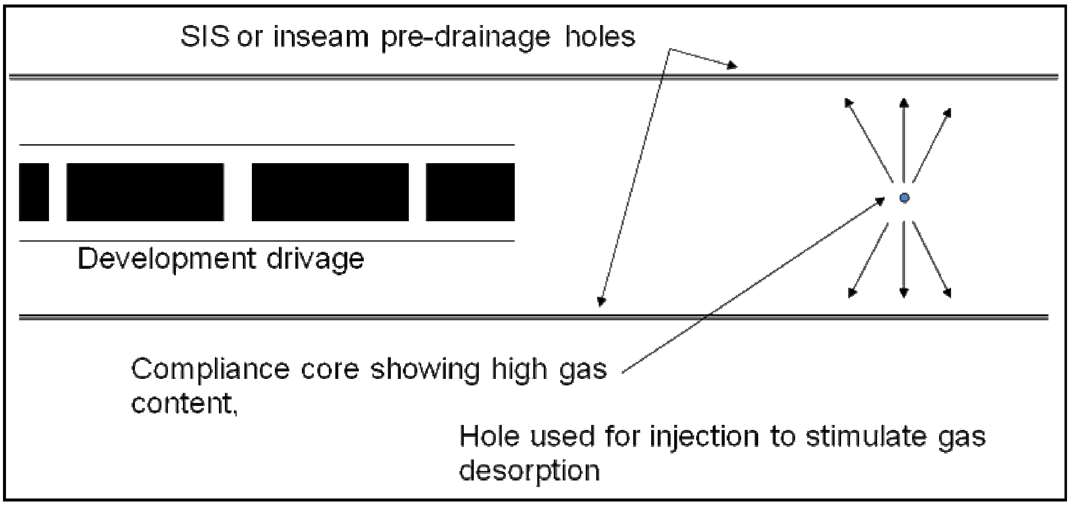

Figure 4 - Use of a compliance borehole for localised enhanced gas drainage

Underground Gas Drainage Applications

Underground drainage is often conducted where there is inadequate lead time for surface drainage; where access to surface drilling locations are impractical; or where depth of cover makes drilling cost prohibitive. Due to practical considerations underground gas drainage holes are typically 300-600m long. The restriction of the hole length has implications for the drainage time available. The reduced gas drainage time is generally offset by reducing spacing between drainage holes (typically 50-70m). In coal mining environments where U/G gas drainage is conducted to manage outbursts similar problems may arise as described above. An enhanced gas drainage system utilizing an underground gas drainage layout may be feasible using alternate drainage holes as injectors (Figure 5). Such an approach would be subject to problems associated with highly heterogeneous seam conditions i.e. localised faulting allowing rapid breakthrough of the injectant to the producing hole. Furthermore the proximity of the hole collars may lead to rapid breakthrough and reduce flow at inbye sections of the hole.

In a gas drainage environment of very low permeability (<0.01md) achieving two phase drainage condition may be difficult (the permeability being so low that water flow in the cleat is minimal). In such conditions an injector/production borehole arrangement may not be effective; an alternative may be to adopt a 'huff-puff' process of cyclic injection then bleeding off of the injectant/seam gas mix. The procedure would be continued until the localised permeability had improved to allow an injector/production borehole arrangement.

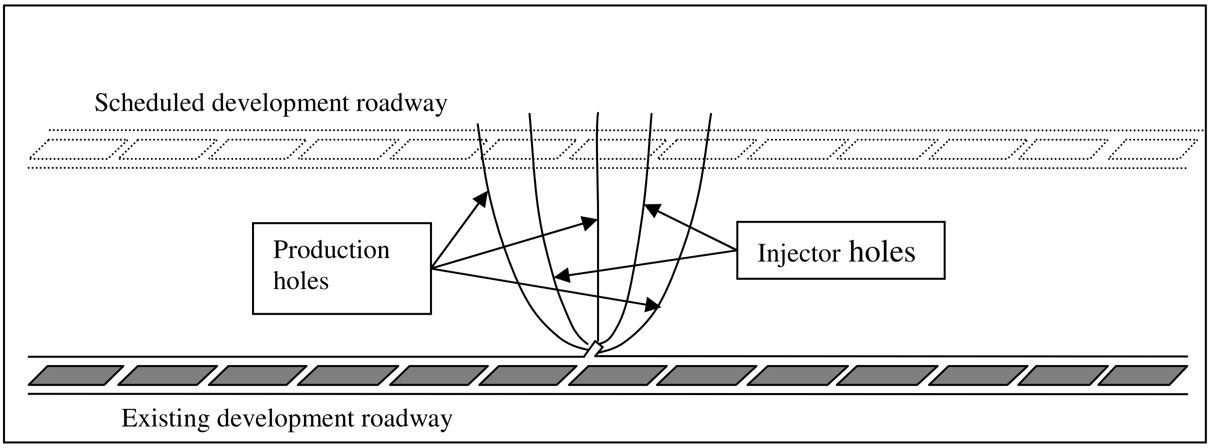

Figure 5b - Schematic layout for an underground enhanced gas drainage layout

Injector Operational Considerations

The operational pressure of an injector is typically close to hydrostatic pressure in the reservoir. In a reservoir that already undergone some pressure depletion such as an existing surface gas drainage installation, the pressure of the injectant gas would be greater that the pore pressure of the region to be subject to enhanced gas recovery.

Bowen basin coal mine surface gas drainage operations have typically 150-250m of cover. Injectant pressures of 1-2 MPa would be feasible where primary production had been undertaken. Illawara coal mines typically operate in the Bulli seam at initial gas contents of 10-20 m^3/t. Hargraves (1995) reported that insitu gas pressures of 4 MPa have been measured at Appin Colliery, Lama (1995) states pressures of up to 4.6 MPa have been measured underground in the Bulli seam.

Infrastructure

Existing underground compressed air ranges operate at ~700 kPa using victualic type couplings. Operating a compressed air victualic range to transport compressed nitrogen would be feasible up to 1.2 MPa. At the depth of workings of most Australian mines, a gas drainage system in primary production could be expected to have a pore pressure of less than 1.2 MPa.

The surface facilities of typical SIS wells use ANSI 300 fittings, with a maximum pressure rating of 4.65 MPa (675 psi). Compressors are available for operation at 3.4 MPa and 420 l/s.

Application of an injectant gas would be comparatively simple at pressure less than 1.2 MPa for underground operation and up to 3.4 MPa for a surface installation. Higher operating pressures may be possible but would require purpose designed standpipes and delivery pipework for underground applications, and wellhead arrangements and compression facilities for surface applications.

Injectant gas source

Coal mines in the Bowen Basin routinely use inert gasses to accelerate the transition of newly sealed goafs to non-explosive atmospheres. The inertisation involves injection of nitrogen or flue gas to displace or dilute oxygen in goaf regions. Facilities for the production of inert gasses (routine and emergency) include liquid nitrogen systems, membrane nitrogen systems and flue gas generators.

Liquid nitrogen systems are comparatively expensive and suffer from cryogenic (hazardous goods) transport limitations. The latter issue would be particularly significant for continuity of supply to Bowen Basin mine sites.

Existing flue gas generators are not directly suitable for enhanced gas recovery at mine sites. Flue gas contains nitrogen as well as CO_2 however requires a catalytic converter to remove residual oxygen and scrubbers to remove carbonic acid. Use of flue gas as an injectant in a coal mine enhanced gas recovery system would require careful management to avoid generating problematic CO_2 concentrations in the coal reserve.

Membrane nitrogen filtration systems are in use at mines in the Bowen Basin and Hunter valley. The "AMSA" membrane units generate nitrogen at ~97% purity and an outlet pressure of 900 KPa. Units in use in the mining industry have flow rates of 120 and 500 l/s. Use of membrane systems currently at mine sites is considered feasible as a source of injectant gas for enhanced gas recovery. The membrane units are self contained and have good reliability and require only a power supply to operate (Figure 6).

Figure 6 - "AMSA" Membrane filter at a Hunter Valley Coal Mine

SUMMARY

Enhanced gas recovery in coal mine gas drainage operations has the potential to be a step change in drainage practice. Drainage in low permeability conditions and low residual gas level objectives, which had hitherto been impractical, appears technically feasible.

Implementation of an enhanced gas recovery scheme at a minesite where primary gas production is being conducted (pressure depletion) and seam pore-pressures are below 900 kPa offers no insurmountable problems.

The next stage of this research will involve detailed site charaterisation and field trial preparation with a view to undertaking a field trial mid 2009.

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REFERENCES

Black, D. (2007). Gas Management Challenges at Westcliff Colliery, [online]. From: http://www.uow.edu.au/eng/outburst/presentations_publications/outburst_2007/DBlack-07.html [Accessed 29 October 2008].

Brunner, D, Schwoebel, J (2007). In-mine methane drainage strategies. *American Longwall,* May pp 38-39.

CSIRO Petroleum (2003). SIMED-II - Multicomponent Coalbed Methane Gas Simulator, Procedures Manual.

Gray, I. (1987). Reservoir Engineering in Coal Seams: Part 1-The Physical Process of Gas Storage and Movement in Coal Seams. SPERE (February 1987) 28.

Hargraves, A J, (1995). Some properties of coals containing gas and some related incidents, *International Symposium cum Workshop on Management and Control of High Gas Emissions and Outburst in Underground Coal Mines 2005,* Wollongong, Australia.

Lama, R. D. (1995). Safe gas content threshold value for safety against outbursts in the mining of the Bulli seam. *International Symposium cum Workshop on Management and Control of High Gas Emissions and Outbursts in Underground Coal Mines 2005*, Wollongong, Australia.

Mavor, M J, Gunter, W D, (2004). Secondary Porosity and Permeability of Coal vs. Gas Composition and Pressure. *SPE Annual Technical conference and Exhibition*. Houston. SPE 90255.

Mavor, M J, Gunter, W D and Robinson, J R, (2004). Alberta Multiwell Micro-Pilot Testing for CBM Properties, Enhanced Methane Recovery and CO2 Storage Potential. *SPE Annual Technical Conference and Exhibition 2004*. Houston. SPE 90256.

Packham, R, (2005). Experience With Production in a Gassy Environment, Oaky North Mine, in *Proceedings of 8th International Mine Ventilation Congress 2005*, Brisbane, Australia.

Palmer, I, and Mansoori, J, (1998). How Permeability Depends on Stress and Pore Pressure in Coalbeds: A New Model. *SPE Annual Technical Conference and Exhibition*, Denver, SPE 52607.

Puri, R, and Yee, D (1990). Enhanced Coal Bed Methane Recovery. *SPE 65th Annual Technical Conference and Exhibition*, New Orleans. SPE 20732.

Reeves, S and Oudinot, A, (2004). The Tiffany Unit N_2 – ECBM Pilot: A Reservoir Modelling Study. Topical Report U.S. Department of Energy, DE-FC26-0NT40924.

Reeves, S, Davis, D,W and Oudinot, A,Y, (2004). A Technical and Economic Sensitivity Study of Enhanced Coalbed Methane Recovery and Carbon Sequestration in Coal. Topical Report, U.S. Department of Energy, DE-FC26-00NT40924.

Robertson, B. (2008). Personal communication, R Packham, 10 November.

Seidle, J P, Jeansonne, M, W and Erickson,D,J, (1992). Application of Matchstick Geometry to Stress Dependant Permeability in Coals. *SPE Rocky Mountain Regional Meeting, Casper,* Wyoming, SPE 24361.

Shi, J Q and Durucan, S, (2005). A Model for Changes in Coalbed Permeability During Primary and Enhanced Methane Recovery, SPE 87230.

Shi, J Q, and Durucan, S (2004). Drawdown Induced Changes in Permeability of Coalbeds: A New Interpretation of the Reservoir Response to Primary Recovery, *Transport in Porous Media* **56**(1): 1-16.

Shi, J Q, Durucan, S and Fujioka, M, (2008). A reservoir simulation study of CO2 injection and N2 flooding at the Ishikari coalfield CO2 storage pilot project, Japan. *International Journal of Greenhouse Gas Control* **2**(1): 47-57.

Stevenson, M D, Pinczewski, WV and Downey, R A, (1993). Economic Evaluation of Nitrogen Injection for Coalseam Gas Recovery. *SPE Gas Technology Symposium*, Calgary, Alberta, Canada, SPE 26199.

Thakur, P C, (2006). Coal Seam Degasification, in *Handbook for Methane Control in Mining*, (ed: F N Kissell), Chapter 6 pp 85, (National Institute for Occupational Safety and Health: Pittsburgh) Information Circular 9486.

Zuber, M D, (1996). Basic Reservoir Engineering for Coal, in *A Guide to Coalbed Methane Reservoir Engineering*, (ed: J Saulsberry, L P Schafer, and R Schraufnagel) Chapter 3 pp 4 (Gas Research Institute, Chicago) GRI-94/0397.